Carderock Division

Naval Surface Warfare Center

Bethesda, Maryland 20814

CRDKNSWC-HD-0043-03 April 1995
Hydromechanics Directorate
Research and Development Report

Damage Stability Model Test for the Advanced Double Hull (ADH) Program

By
Paul J. Kopp and
Richard Bishop

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CRDKNSWC-HD-0043-03 Damage Stability Model Test for the Advanced Double Hull (ADH) Program

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for Public Release, Distribution Unlimited
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) CRDKNSWC-HD-0043-03	5. MONITORING ORGANIZATION REPORT NUMBER
6a. NAME OF PERFORMING ORGANIZATION Carderock Division, Naval Surface Warfare Center 6b. OFFICE SYMBOL Code 5610	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP code) Bethesda, Maryland 20814	7b. ADDRESS (City, Sate, and ZIP code)
8a. NAME OF FUNDING / SPONSORING ORGANIZATION Office of Naval Research 8b. OFFICE SYMBOL ONR-334	9. PROCUREMENT INTURMENT NUMBER
8c. ADDRESS (City, State, and ZIP code) Arlington, Virginia 22301	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. 62121N PROJECT NO. TASK NO. WORK UNITS ACCESSION NO.

11. TITLE (Including Security Classification)
Damage Stability Model Test for the Advanced Double Hull (ADH) Program

12. PERSONAL AUTHOR(S)
Paul J. Kopp and Richard Bishop

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT	15. PAGE COUNT
Final	Feb 1994 to Oct 1994	April 1995	36

16. SUPPLEMENTAL NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Contine on reverse if necessary and identify by block number)
Damage Stability
Advance Double Hull (ADH)
Model Test
Righting Arm Test
Regular Waves
Roll Decay
Wind

19. ABSTRACT (Contine on reverse if necessary and identify by block number)

A series of dynamic damage stability model tests have been performed on a CG-47 hull form fitted with a double hull test section. These tests were carried out in support of the static and dynamic stability sub-tasks of the Advance Double Hull (ADH) Project. Various combinations of flooding conditions were investigated in regular beam seas, with and without wind. The model was subjected to regular waves ranging from 2.2 to 12.9 feet, single amplitude, with periods ranging from 5.3 to 19.9 seconds. These regular wave tests performed at the Carderock Division, Naval Surface Warfare Center (CDNSWC) in the Maneuvering and Seakeeping (MASK) basin. Calm water roll decay tests were also performed at the MASK while righting arm tests were performed at the adjacent drop tank facility. These test were performed in order to calibrate the static stability and roll damping characteristics of the physical model to those of associated computational models.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT Unlimited	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
22a. NAME OF RESPONSIBLE INDIVIDUAL Paul J. Kopp	22b. TELEPHONE (Including Area Code) 301-227-5119	22c. OFFICE SYMBOL Code 5610

UNCLASSIFIED

CONTENT

Abstract i

Administrative Information 1

Introduction 1

Ship and Model Characteristics 1

Experimental Procedure 2

Righting Arm Test 2

Roll Decay Test 3

Regular Wave Test 3

Instrumentation 4

Description of Analysis 5

Uncertainty Analysis 7

Results 9

Summary and Conclusions 10

References 31

FIGURES

1. Body Plan 11
2. Inner Shell and Inner Foam Inserts 11
3. Outer Foam Insert 12
4. Inner Hull Insert as Placed in Model 12
5. Schematic Diagram of Righting Arm Test Apparatus 13
6. Photograph of Model in Righting Arm Test Apparatus 13
7. Righting Arm Curve Comparison: Intact Condition 14
8. Righting Arm Curve Comparison: U-Tank, Outer Shell Damaged 14
9. Righting Arm Curve Comparison: U-Tank, Outer and Inner Shells Damaged 15
10. Righting Arm Curve Comparison: J-Tank, Outer Shell Damaged 15
11. Righting Arm Curve Comparison: J-Tank, Outer and Inner Shells Damaged 16
12. Roll Extinction Data: Intact Condition 16
13. Roll Extinction Data: U-Tank, Outer Shell Damaged 17
14. Roll Extinction Data: U-Tank, Outer and Inner Shells Damaged 17
15. Roll Extinction Data: J-Tank, Outer Shell Damaged 18
16. Roll Extinction Data: J-Tank, Outer and Inner Shells Damaged 18

17. Extreme Roll Response Countours About the Mean, Intact Condition 19
18. Extreme Roll Response Countours About the Mean, U-Tank, Outer Shell Damage 19
19. Extreme Roll Response Countours About The Mean, U-Tank, Outer and Inner Shells Damaged 20
20. Extreme Roll Response Countours About the Mean, J-Tank, Outer Shell Damaged 20
21. Extreme Roll Response Countours About the Mean, J-Tank, Outer and Inner Shells Damaged 21

TABLES

1. Ship Particulars 22
2. Righing Arm Validation Test Error Analysis 23
3. Roll Decay and Regular Wave Test Error Analysis 24
4. Measured and Predicted Static Heel Angles and Deck at Edge Immersion Angles 25
5. Linear Damping Coefficients and Mean Natural Roll Periods 25
6. Regular Wave Test Results, No Wind 26
7. Regular Wave Test Results, With Wind 28

ABSTRACT

A series of dynamic damage stability model tests have been performed on a CG-47 hull form fitted with a double hull test section. These tests were carried out in support of the static and dynamic stability sub-tasks of the Advanced Double Hull (ADH) Project. Various combinations of flooding conditions were investigated in regular beam seas, with and without wind. The model was subjected to regular waves ranging from 2.2 to 12.9 feet, single amplitude, with periods ranging from 5.3 to 19.9 seconds. These regular wave tests performed at the Carderock Division, Naval Surface Warfare Center (CDNSWC) in the Maneuvering and Seakeeping (MASK) basin. Calm water roll decay tests were also performed at the MASK while righting arm tests were performed at the adjacent drop tank facility. These tests were performed in order to calibrate the static stability and roll damping characteristics of the physical model to those of associated computational models.

ADMINISTRATIVE INFORMATION

This work was funded by the Office of Naval Research (ONR-334) and is submitted as part of the deliverables from Task 14 of the Advanced Double Hull Technology Project (RH21S11) of the Surface Ship Technology Block Program (PE0602121N).

INTRODUCTION

In support of the Damage Stability Task (Task 14) of the Advanced Double Hull (ADH) Project, a series of test were conducted on an existing CG-47 model, modified with a double hull test section. The test section was constructed in a such a way that different flooding geometries could be simulated. The test program was divided into three parts; righting arm validation tests, roll decay tests, and regular wave tests. The righting arm validation tests were conducted to allow measurement of the static intact and damage stability characteristics of the model and comparison to the stability characteristics computed by the Ship Hull Characteristics Program (SHCP) version 4.11 [1]. Roll decay tests, conducted in calm water, were performed to determine the roll damping characteristics and natural roll period of the model in the intact and damage conditions. The final portion of the test program was testing in regular waves of varying height and period, with and without a beam wind.

SHIP AND MODEL CHARACTERISTICS

The model experiments were carried out using a 1:24.824 scale model of the baseline CG-47 hull form designated by Carderock Division, Naval Surface Warfare Center (CDNSWC) model number 5480. A body plan of the hull form is illustrated in Figure 1. Principle characteristics are listed in Table 1. The model was appended in all cases with rudders, propellers, and bilge keels. The original model was constructed with a solid 3/4" plywood

bulkhead located at Station 8.32, keel to deck at edge. This longitudinal position corresponds roughly to a main transverse bulkhead within the full scale vessel. An aft bulkhead was installed in the model at Station 11.34 which also corresponds to a main transverse bulkhead within the full scale ship. The space between bulkheads on the model is equivalent to two primary longitudinal compartments.

In order to simulate the space between the inner and outer hull shells on a double hull vessel, an inner fiberglass hull shell was constructed from the hull offsets, scaled in a direction perpendicular to the existing outer hull surface. A spacing between inner and outer shells of 6 feet full scale was selected. As a watertight seal between the transverse bulkheads and the inner shell was not feasible, an insert was constructed from 3 inch thick styrofoam sheets. The insert would fit inside of the inner shell and permeate the space, effectively preventing flooding. A similar insert was constructed to fill the starboard side of the space between inner and outer hull shells. Applying the correct combination of inserts, a variety of flooding scenarios could be tested. Figure 2 shows a photograph of the fiberglass insert and inner foam insert side by side. The insert to be placed between the shells is shown in Figure 3. Figure 4 shows the inner shell insert placed in the model. Three wooden support bars spanning the model breadth are visible. In addition to allowing the fixture to be secured to the hull, the supports also provided stiffness to the fiberglass shell.

The final modifications to the model included drilling one 2-1/2" hole in the inner shell and another in the outer hull shell at Station 10 to the port of the centerline. Plugs were created from the removed material so that the holes could be covered and opened by test personnel as needed. In addition, small diameter stainless steel rods were fastened to the hull at the bow and stern on centerline, approximately 1 inch below the undamaged upright waterline. These rods allowed the model to be constrained from drifting and yawing excessively in the MASK basin while the model was exposed to waves and/or wind. Soft spring shock (bungee) cord was used to restrain the model from drifting, but allowed some freedom of motion in sway and yaw. Roll, pitch, and heave were not significantly effected though.

EXPERIMENTAL PROCEDURE

The test program was divided into three primary phases; righting arm validation tests, roll decay tests, and regular wave tests. Each test series was performed on the model in the intact condition as well as several damaged conditions. The damage conditions which were tested included U-tank and J-tank geometries, with and without inner hull shell damage (i.e., inside foam insert used).

RIGHTING ARM TESTS

Righting arm tests were performed at the drop tank facility adjacent to the MASK basin. The intention of these tests was to determine the static stability characteristics of the model in the intact and damaged conditions. Comparisons could then be made against stability characteristics calculated using the SHCP computer program. Since the SHCP calculated stability characteristics were to be used in the dynamic stability computational model being developed for the ADH project, this step was vital.

Prior to testing, the model was fitted with a 3/16" thick aluminum circular fixture 41 inches in diameter, centered about the model center of gravity and located at station 10. Bilge keels were removed from the model in order to accommodate the ring. A pair of wire rope lines were attached to opposite sides of the outside diameter of the ring fixture and lead around the circumference. One line was lead down into the drop tank, through a pulley and back up to load cell which was attached at the other end to a hand crank winch. The second line was brought up directly to another load cell which was also attached to another hand crank winch. Both hand cranked winches were tied to a wooden frame constructed over the drop tank. A schematic drawing of the apparatus used is shown in Figure 5. A photograph of the model and apparatus in use is shown in Figure 6. Using both winches in unison, an approximately equal pair of external moments could be applied to the model, forcing a heel angle. Using the diameter of the ring, the measured loads from the load cells, and a deck mounted inclinometer to measure heel angle, points on the righting arm curve were obtained. When testing the damaged conditions, the model was allowed to flood freely and reach steady flood conditions before a data point was taken.

ROLL DECAY TESTS

Roll decay tests were performed at the MASK facility. These tests were used to quantify roll damping characteristics and the natural roll period for the intact and damaged conditions. Prior to testing, the model was fitted with bilge keels and attached to the shock cord restraints. Previous tests (documented in limited distribution resports) have shown that roll damping and roll response motions are not significantly effected by the presence of the restraints. The test was performed by CDNSWC personnel heeling the model by hand and releasing. The model was allowed to roll freely while roll angle measurments were recorded via digital computer and analog strip chart recorders. In the damage conditions tested, the compartments were allowed to flood freely prior to initiating roll decay measurements and free communication of flooding water with the basin was allowed during the test.

REGULAR WAVE TESTS

Regular wave tests were performed with the model as configured for the roll decay tests. Regular (long crested) waves were generated with the basin's long set (north side) of pneumatic wavemakers. A range of wave height and period combinations was used to excite model roll response. The wave conditions used were selected based on recommendations by Dr. William McCreight of CDNSWC, who was developing the dynamic stability computational model and performing motion simulations.

The manner in which waves were applied to the model was also recommended by Dr. McCreight. The computational model used a time domain motions simulator which would impulsively start the simulated waves, i.e. no amplitude ramping. Several roll cycles after the start of the waves, they were terminated suddenly. Duplicating this exact behavior in the testing tank is not possible, however the following method was used to mimic it. With the wavemakers turned off (calm water), the model was allowed to reach steady flooding conditions (if damage condition used). The data collection computer was instructed to begin collecting data, and the wave makers were started. After approximately ten or twelve roll cycles were recorded after the waves had reached the desired

amplitude, the wave maker was turned off. The model was allowed to respond while the ambient wave conditions returned to calm water. The data run was then terminated.

Wind was generated using a large diameter two bladed propeller powered by an electric motor drive. For both the intact and damaged cases, the model was positioned approximately 50 feet in front of the fan. The fan slipstream blew across the model from starboard to port with a slight downwards direction. Using the stability characteristics calculated from SHCP and a known upright wind heeling arm in 100 knots beam wind [2], a static wind loaded heel angle was calculated. With the fan running at moderately high speed, lateral windage was added to the model superstructure until this calculated steady heel angle was achieved. This "calibration" procedure was repeated for a nominal full scale wind speed of 38.4 knots, where the windage was kept constant but the fan speed reduced until the calculated steady heel angle was achieved. However, the upright heeling arm for the reduced wind speed of 38.4 knots was estimated by linearly scaling the 100 knot wind upright heeling arm. The static wind loaded heel angle was then calculated using this estimated upright heeling arm and the SHCP stability characteristics as performed for the 100 knot case. The reduced wind speed value of 38.4 knots was determined according to U.S. Naval damage stability criteria [3].

INSTRUMENTATION

Through the course of the test program, a variety of test instruments and sensors were used in collecting data. For the righting arm test, the two 1000lbf load cells were used. Each load cell was connected directly to a digital display which directly indicated pounds force measured (i.e., calibration factor of 1 lb./v). Each load cell was calibrated using suspended weights of known mass. The standard error of the estimates from the calibration data was ±0.0114 lbf. The roll angle inclinometer used was adapted from an electronic level, originally attached to a Stanley Tools Series 200 "SmartLevel". According to the consumer product information provided in the packaging, the inclinometer is accurate to ±0.1 degrees within ±1 degree of level and ±0.5 degrees for larger angles. However, the electronic level is limited to a range of ±30 degrees. In order to compensate for this, a triangular wooden block with a 30 degree angle was used as a mounting base when the heel angle went beyond approximately 25 degrees. This offset has been corrected in the final data.

For the roll decay test, roll angle was measured using a two axis solid state angular sensor manufactured by Watson Industries, model number ADS-C232-1A. This sensor is reported to be accurate to ±0.3 degrees static, ±2% of reading with an operating range of ±30 degrees (20% overrange provided). Angular rates are also provided by the sensor but were not utilized. Angular outputs of the sensor are ±10VDC at ±30 degrees. The outputs were lead to an analog to digital converter (A/D) adapter card (ISA bus) housed inside a personal computer using an Intel i486DX25 processor. The A/D board was manufactured by Scientific Solutions, Inc. and was a Lab Master DMA model. This card uses a 12bit A/D and is accurate to ±0.03% over the range of ±10V (using a hardware gain of 1). The board is capable of 40000 samples/second/channel with a sample-and-hold aperture uncertainty of 10 nsec.

The regular waves test used the same roll and pitch angle sensor and the same A/D and computer as described above. Heave acceleration was measured by a Donner model 4310 linear accelerometer. This

accelerometer is accurate to 0.1% over a range of ±35G's. Signal output is ±7.5V over the operating range. Before being connected to the A/D input, the output signal was amplified. The wave amplitude measurements were provided using an in air ultrasonic pulsed sonar sensor, model LM4000, manufactured by Western Marine Electronics, Inc. The sensor was attached to an aluminum pole extending approximately 50 feet from the side of the MASK basin, adjacent to the model, and approximately 3 feet above the calm water surface. The sonic sensor has an accuracy of 0.5% over the operating range, normally set to ±16 inches. Signal output is nominally ±1V over the operating range and was passed through a signal amplifier before input to the A/D board.

DESCRIPTION OF ANALYSIS

The data collected durring the righting arm tests was entered into a spreadsheet program for data analysis and graphical presentation. Calculated righting arm data, from SHCP, were also into the spreadsheet for comparison to the experimental data. The experimental data collected included the port and starboard load cell force measurements and the heel angle obtained from the electronic level. Righting arm values were obtained from the load cell measurements by summing the port and starboard force values and multiplying by the radius of the circular aluminum ring placed around the model. This produced the value of the moment about the center of the ring, as applied to the model. The moment was then divided by the model weight to yield the model scale heeling arm, which was assumed to be equal to the model righting arm. This also assumed that the center of the ring and the center of gravity of the model were always coincidental. Model scale righting arm values were then converted to full scale by multiplying by the model scale factor. Direct comparisons with the SHCP computed righting arms were then possible.

Roll decay results were analyzed according to the method discussed in [4]. According to this method, successive pairs of maximum or minimum values in the roll angle are used to compute the decrement (difference between values) and mean swing (average value). These data pairs (decrement, mean swing) are plotted to obtain the roll extinction curve. The data points are then curve fit to a polynomial function (with mean swing as the independent variable), usually of order three, where the coefficients obtained from the curve fit are directly related to the dimensional nonlinear roll damping coefficients (β^*_n , n=0,...)by a factor of π. It is customary to force the polynomial curve to go through the origin, which implies that the zeroth order coefficient is identically zero. This should be true anyway, even for an asymmetrical flooding condition that decays in roll to a non-zero heel angle, since the decrement in roll angle always approches zero (i.e. steady state). The mean roll period was also obtained from the roll angle signals as the time difference between successive pairs of maximum or minimum roll angles.

The methodology for roll decay test analysis described above is slightly different from the usual method used at CDNSWC for roll decay tests. Normally, the nondimensional roll damping coefficient, n, is calculated[1] and

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[1] roll damping coefficient, $n=\ln(\phi_{(n+1)} / \phi_n)/2\pi$. Also, $n = \omega_\phi^2 B_{44} / 2 C_{44}$ where B44 and C44 are the dimensional roll damping and and restoring force coefficients (both are functions of ω_ϕ) respectively and ω_ϕ is the natural roll period.

plotted against mean roll angle. This operation requires a division of experimental data points and a natural log of the result of the division. An uncertainty analysis of this data reduction method reveals that the uncertainty in n is proportional to the uncertainty in roll angle and a nonlinear function of $\phi_{(n+1)}$ and ϕ_n. This behavior results in an uncertainty in n that is a magnification of the uncertainty in roll angle. However, the method used in this analysis essentially involves only sums and differences or roll angle measurements. A similar uncertainty analysis of the data reduction method shows that the uncertainty in roll decrement (the dependant variable), is just the uncertainty in the roll angle measurement. Curve fitting the data, using either method introduces similar uncertainty, expressed as the standard error of the estimate from the curve fit. Using the dimensional roll damping for comparisons, as done in this investigation, is acceptable since it is the relative change between conditions that is important.

Using the usual CDNSWC method, the plot of n versus average roll amplitude can indicate the degree of nonlinearity in roll damping by the slope of the curve (higher slope, greater nonlinearity). The linear roll damping is determined by the intercept of the curve at zero mean roll. The method used in this investigation provides the linear roll damping coefficient as the slope of the curve of roll decrement versus mean swing angle. The degree of curvature indicates the degree of nonlinearity in roll damping.

Regular wave data was processed in a multi-step manner. First, the roll angle and wave height time histories were used to determine the start and stop times of the steady state condition, between the wave maker start up and stop commands. This process was performed automatically using a 5 point moving average on the roll angle, wave height, and heave acceleration signal envelopes (peaks and troughs) and determining starting and ending times when the moving averages exceeded the signal variance. These starting and ending times were considered to represent the extents of the quasi-steady state condition. Several spot checks were used to manually verify this procedure by using strip plot charts of the collected data. A second data analysis was performed on the previously determined steady state portion of the test time histories collected. For this second pass, the roll and wave height signals and their signal envelopes were analyzed to produce average values of the signal and envelope as well as the variance of the signal and signal envelope.

The average values of the steady state roll angle envelopes were corrected for the mean steady state roll angle (represented by the roll signal average value) and arranged into a two dimensional table according to wave height and period. This table was used to construct a non-uniformly spaced grid of points from which countours of constant average extreme roll angle were produced. In the process of creating the countour plots, no data smoothing was performed.

Linear systems theory states that the maximum response occurs at the natural roll period (and at some value of wave height) and tapers off as the period of excitation (waves) is changed from the natural period. Likewise, the maximum roll response will occur at some particular wave height (up to a limit for non-breaking waves) at the natural roll period. Holding period constant, as the wave height is decreased below the wave height of maximum roll response, the roll response decreases.

UNCERTAINTY ANALYSIS

In an experiment, no measurement is truly certain. Errors, inaccuracies and loss of precision can occur and propagate through data reduction. Uncertainty analysis is the methodology used to determine the effects of errors and error propagation on the experimental results [5]. There are two types of errors; bias and precision errors. Bias, or fixed errors, remain constant while precision , or random errors will vary. There are three primary sources of error to be concerned with; calibration, data acquisition, and analysis errors.

For the righting arm test, a calibration of the load cells was performed using a standard set of precision weights. The precision error was obtained from the standard error of the linear curve fit to the calibration data points and as the load cells were used in straight line tension only, alignment errors were assumed to be zero. This represented the calibration error for each load cell used. The accuracy of the load cells was 0.02% of the operating range of the load cells. This is a bias which was considered to be the only data acquisition error from the righting arm test. Data analysis errors are the result of performing mathematical operations on collected data. Righting moment is the product of the ring diameter and the two load cell measurements at a measured heel angle. The ring was fabricated by the CDNSWC metal shop and was estimated to be accurate to within 1/16" (radius). However, the model center of gravity and the center of the circular ring may not always be identical. The total bias in diameter was therefore estimated to be ±1.5".

Bias errors in the inclinometer were considered to be negligible (as compared to the precision). The wooden block used to adjust for heel angles beyond 30 degrees has been assumed to have a bias of ±0.5 degrees and a precision of ±1 degrees. Alignment errors in the mounting of the inclinometer, and the associated wooden block, were estimated to be no more than 3 degrees. This alignment error does not act linearly on the heel angle measurement though. It is the trigonometric component of the sensor in the plane of rotation, which is given by the cosine of the alignment error. The effective alignment error, for the purpose of uncertainty analysis, is the difference between 1 and the cosine of the gross alignment error (±3 degrees), or ±0.14% of the measured heel.

Table 2 represents the righting arm validation test error analysis summary. The only experimental errors reported were calibration errors (random) and load cell accuracy errors (bias). These were used to determine the 95% and 99% confidence intervals for the force readings obtained. However, those confidence intervals are not very useful. The analysis errors shown include the bias error in ring diameter (not really an analysis error, shown here for easier presentation) and the errors due to the summation of the force readings (bias and random). The total analysis error has been obtained from the root sum of the squares of the force summation errors and the ring diameter errors. Also shown in the experimental errors section is the error analysis values for the inclinometer measurements (heel angle). The 95% and 99% confidence intervals for the righting arm and heel angle, shown at the bottom of the table, determine the error "radius" about each data point presented in the righting arm plots discussed in the results section of this document. All confidence intervals shown assumed a student's t-test value of 2.

For the roll decay and regular wave tests, the same instruments were used and hence, the uncertainty analysis is identical. The bias error for the Watson meter used for roll angle was 0.3 degrees with a precision error of 0.6 degrees. Any calibration errors are assumed to be included in the precision error. Errors due to misalignment are

proportional to the root sum squared of the unitary difference of the cosine, i.e. (1-cos ψ) of the alignment error in the horizontal and vertical planes, where ψ is the misalignment angle. It has been assumed that the mounting of the gauge is accurate to within ±3 degrees in either plane, which represents an alignment error of approximately ±0.2% of the measured roll . The heave accelerometer has been assumed to have no bias error and a precision error of less than 0.1g (includes any calibration errors). Alignment errors were computed in a similar manor to those for the roll angle sensor. The wave probe was also assumed to have no bias error. The precision error was 0.16 inches and there was no calibration data available for inclusion. Alignment errors for the sonic probe are complicated due to the nature of the signal reflection from the moving water surface[2]. It has been assumed that alignment errors were insignificant with respect to the precision error. The data collection computer used a 12bit A/D converter card. This means that any voltage is represented by 11 bits and one sign bit. The resolution was therefore $10/2^{11}$ volts, or ±0.00488 volts. Multiplying this value by the calibration factor used for each data channel yields the dimensional bias error for each channel.

Analysis errors for the roll decay and regular wave tests are different from each other. For the roll decay test, only the roll angle signal is used. Errors in the calculated natural period (time scale) were due to the sampling rate of the data acquisition system and can be up to one sample period in either direction (±1/20 seconds). Other timing errors in the A/D conversion process due to the sample and hold circuitry were considered insignificant when compared to the sample rate utilized. The reported roll periods for each damage condition are actually the average of all measured intervals between successive maximum/minimum values (crests/troughs) in the recorded roll signal for that condition. Period information for each run and each condition was averaged separately, and the variance of periods was also separately computed. The maximum variance of the measured period values for all runs was used to represent the random error in the measurement. Roll angle data was reduced using only sums and differences between successive peak roll angle values and then performing a polynomial curve fit to the data. The worst case standard error of the fits for each test case has been reported as the precision error due to data reduction.

Data reduction and analysis of the regular data, as previously described, involved the determination of the steady state portion of the data runs. The effect of this on the uncertainty of the results produced by further analysis is not directly quantifiable. The uncertainty in the analysis performed on the steady state portion of the data runs is contained in the variance of the signals analyzed.

Table 3 represents the summaries of the roll decay and regular wave test error analysis. No separate calibration errors are listed as they were assumed to be included in the precision error listed as a zero reference error. Known levels of bias error have also been shown as zero reference errors. The total calibration errors and data

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2 The historical experience with sonic probes to measure wave height in the basin has shown a tendency in the signals acquired to be prone to seemingly random "drop-outs" and "spikes". The period of occurrence is too long to be a major problem, however it is an annoyance to the analyst who must remove or smooth the renegade data points. No known investigation has ever been performed on the precision or accuracy of sonic measurements of water waves. The error in the wave height measurement has been assumed to be less than ±0.25 inches model scale.

acquisition errors were used to determine the 95% and 99% confidence intervals for the readings obtained. All confidence intervals assumed a student's t-test value of 2.

RESULTS

Results of the righting arm validation tests are shown in Figures 7, 8, 9, 10, and 11 for the intact, U-tank (with and without internal shell flooding), and J-tank (with and without internal shell flooding) conditions. Table 4 shows the measured and predicted static heel angles and deck at edge immersion angles. In all cases, the SHCP model underestimates the righting arm. The intact condition exhibits good agreement between experimental and computed righting arms from 0 to approximately 35 degrees of heel. Larger heel angles have smaller predicted righting arm, though the location of the peak value is approximately correct. The two U-tank geometries also exhibit similar agreement up to moderate heel angles and correctly predicted peak righting arm positions. On the other hand, the J-tank geometry is not predicted very well. The static heel angle is over predicted and the entire righting arm curve is under predicted at equivalent heel angles. The approximate shape is correctly predicted and if the predicted righting arm curve is shifted to match the static heel angles, similar agreement to that of the other geometries is achieved. There were no other influences immediately identified with either the physical or computation models which could have explained such discrepancies for the J-tank geometries. All of the differences observed between calculated and exerimental righting arms were greater than the predicted measurment error listing Table 2.

The roll extinction data from the roll decay tests, are shown in Figures 12, 13, 14, 15, and 16 for the geometries and conditions tested. The results are summarized in Table 5. Only the linear dimensional roll damping coefficients, as well as the percentage change from the intact value and the natural roll periods, are reported. For the symmetric U-tank cases, the damping decreases as the flooding increases from none (intact condition) to full (internal and external shell opening). However, the linear damping for the asymmetric J-tank cases is greater as compared to the intact condition. This result has been observed in another (limited distribution report) damaged stability model test which was performed in part, to investigate roll damping as a function of static heel angle. The natural roll periods determined from the roll decay test data do not show the same trend though. The presence of damage, symmetric or asymmetric, tends to reduce the roll period as compared with the intact case. This was expected due to the additional mass of water trapped within the hull. However, as the extent of damage changes from external shell damage only to internal and external shell damage, the period increases. These results could also be effected by the sloshing of water within the damage test section of the ship model.

Regular wave test results have been shown in Figures 17, 18, 19, 20, and 21 as contour plots of the average maximum roll angles (about the mean heel angle) observed where the regular wave amplitude and period are the independant varriables along the two axis. Data points from the regular wave tests are shown in Tables 6 and 7. Considering only the no wind cases, the peak roll responses do appear to be occurring at approximately the natural roll periods listed in Table 5. These peaks in roll response are not necessarily well defined, indicating the somewhat non-linear nature of ship roll. Absolute global maximums in these roll response contour plots are also not indicated since there were bounds placed on the range of wave conditions tested. It is expected that the global maximum

would occur near the upper limit of physical realizable waves (i.e., non-breaking waves). In the presence of wind, the peak roll response is observed to shift down to a lower value. In the J-tank cases shown in Figures 20 and 21, the peak response appears to be occurring at nearly the same period but at a higher wave height. This may be due to the fact that the J-tank cases were already experiencing a non-zero static heel angle without the presence of wind.

SUMMARY AND CONCLUSIONS

Model tests have been conducted on a CG-47 scale model hull form to determine the static and dynamic stability effects of various double hull damage conditions. These tests have been performed to validate and verify earlier analytic static and dynamic stability studies undertaken for the Advanced Double Hull (ADH) project. The static righting arm tests have shown fair agreement with the earlier computer modeling. Differences were observed for the high (above 35 degrees) heel angle conditions in all cases. Differences between estimated and measured static heel angles for asymmetric flooding conditions were also observed.

Roll decay tests were performed to determine roll damping and natural period differences due to symmetric and asymmetric flooding. Symmetric flooding reduced the linear component of roll damping while asymmetric flooding increased the damping component, as compared to the intact condition. Natural roll periods of all damaged configurations were shorter than for the intact ship. Internal sloshing of water within the test section were concluded to have had an effect on the natural roll period results for the damage conditions tested.

Regular wave tests were performed at specific combinations of height and period, with and without beam wind. Mean values of the extreme roll response, in the quasi-steady state condition, were used to plot contours of roll amplitude as a function of wave height and period. These contours indicated approximate position and magnitude of peak roll response in regular waves. Application of beam wind was observed to shift the apparent peak roll to a lower wave period and larger wave height.

The results of the model tests do not indicate any major inconsistency with other analytic stability studies on ADH vessels. There was no behavior observed in the model during any test to indicate major problems with the ADH concept. However, at the very least, a detailed analytic static stability investigation should be performed on any actual double hull design.

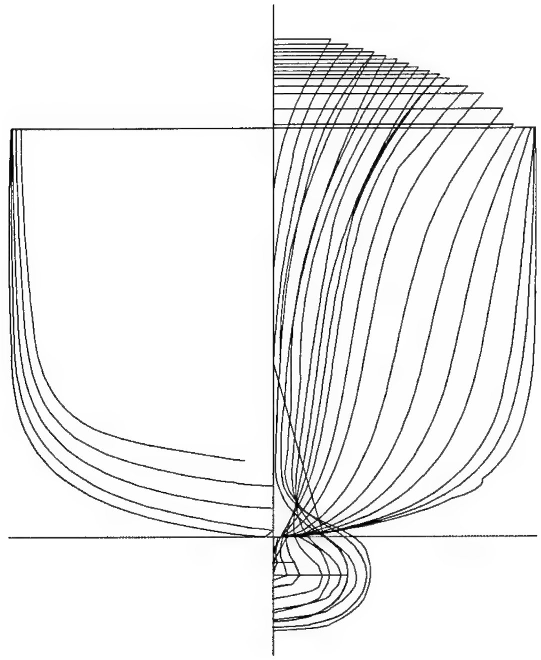

Figure 1. Body Plan

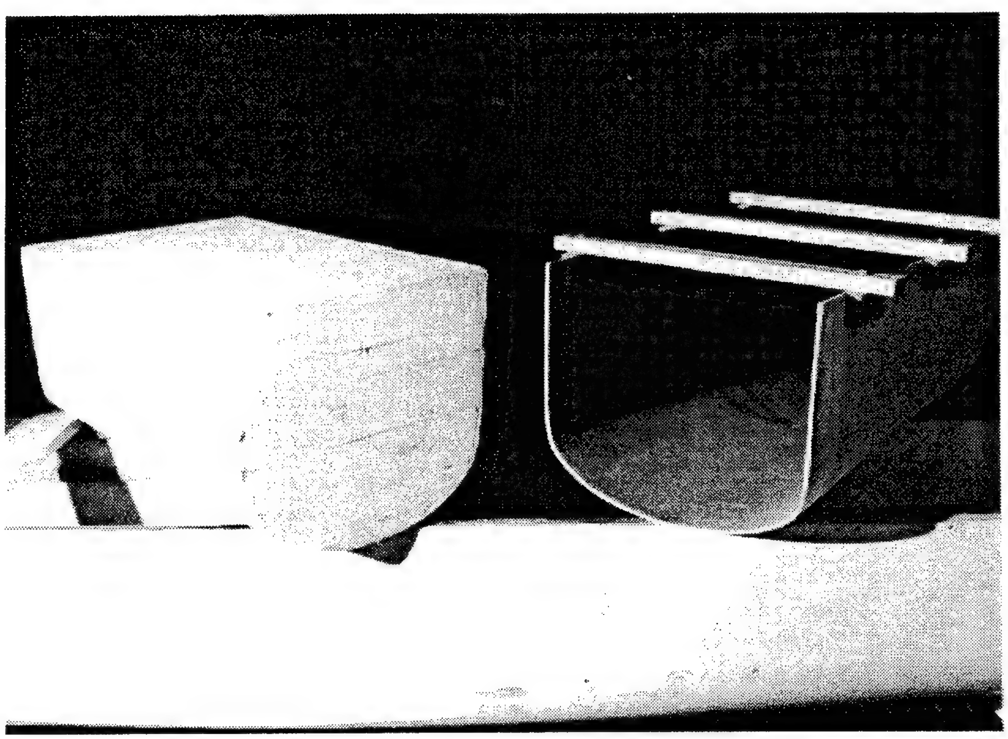

Figure 2. Inner Shell and Inner Foam Inserts

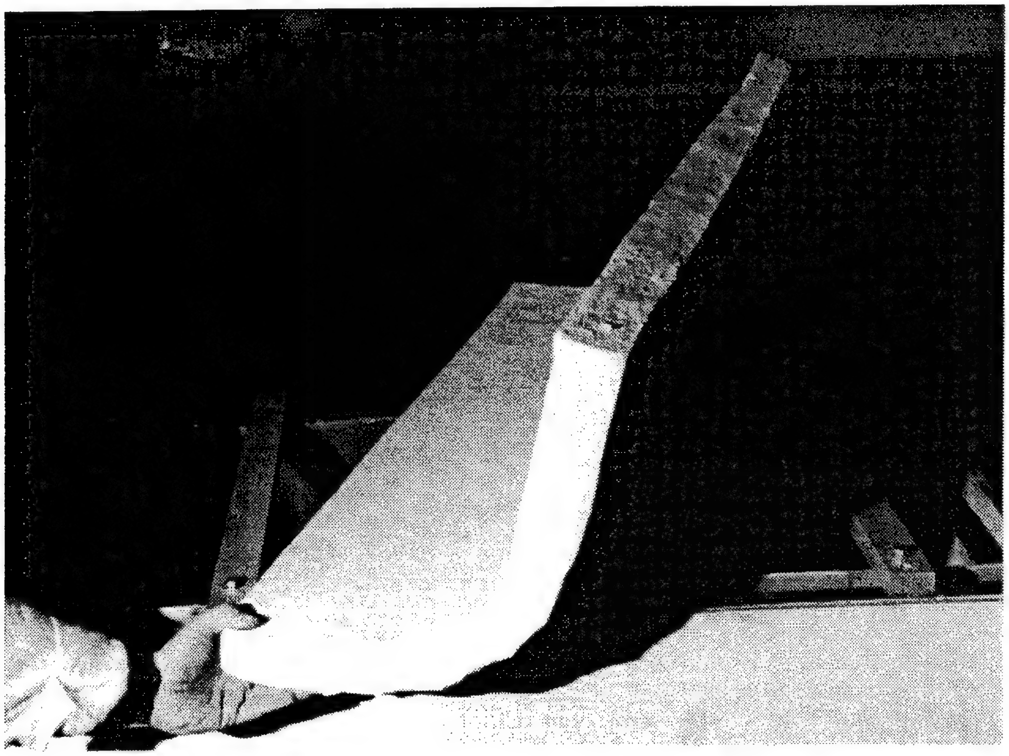

Figure 3. Outer Foam Insert

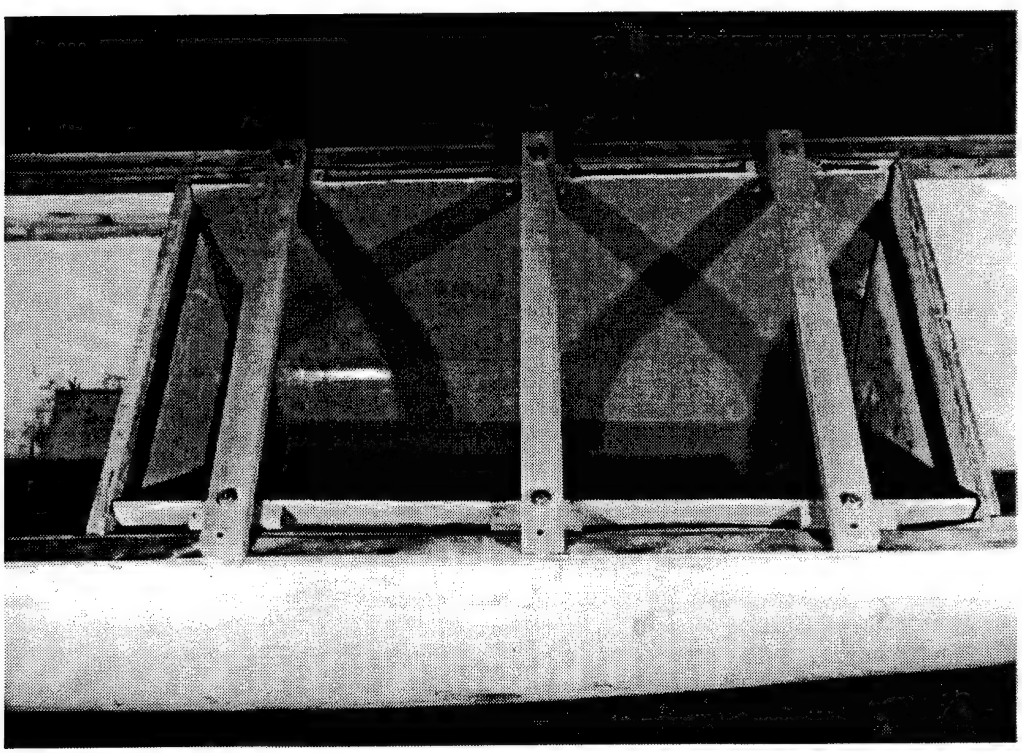

Figure 4. Inner Hull Insert As Placed in Model

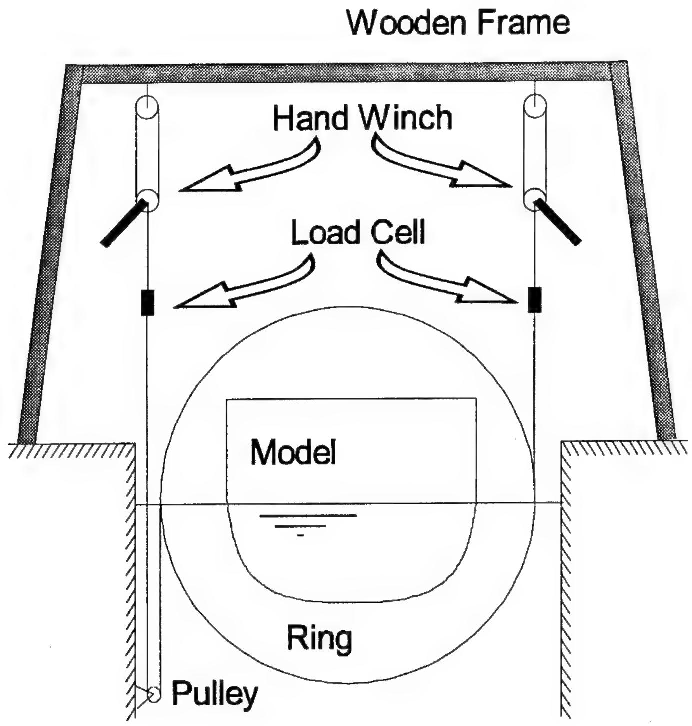

Figure 5. Schematic Diagram of Righting Arm Test Apparatus

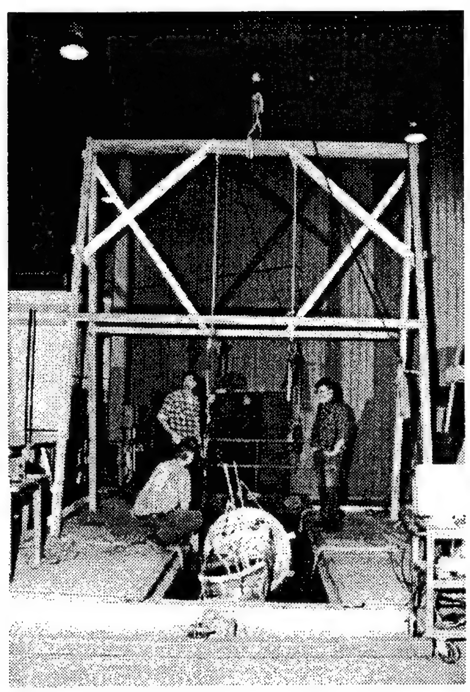

Figure 6. Photograph of Model in Righting Arm Test Apparatus

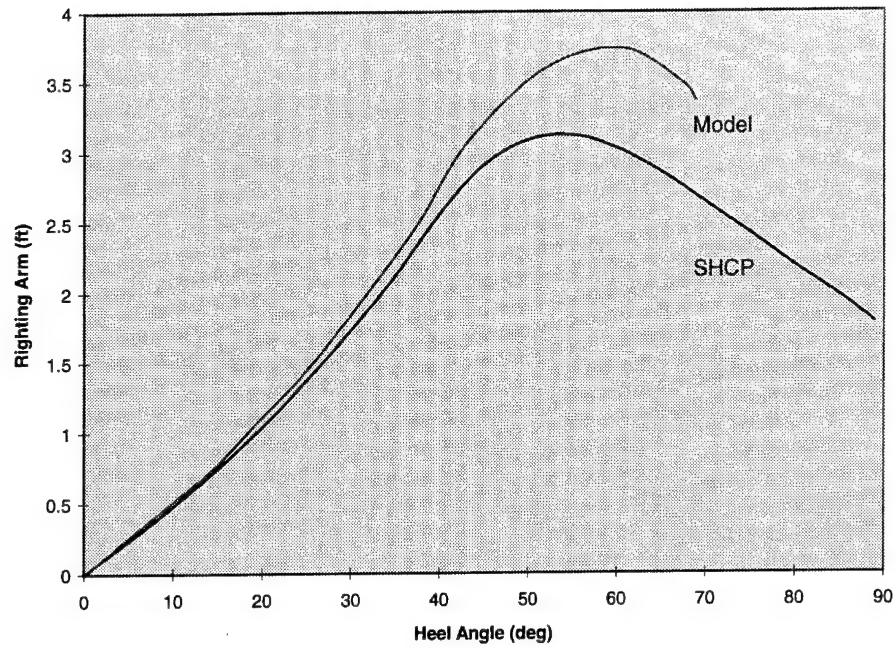

Figure 7. Righting Arm Curve Comparison: Intact Condition

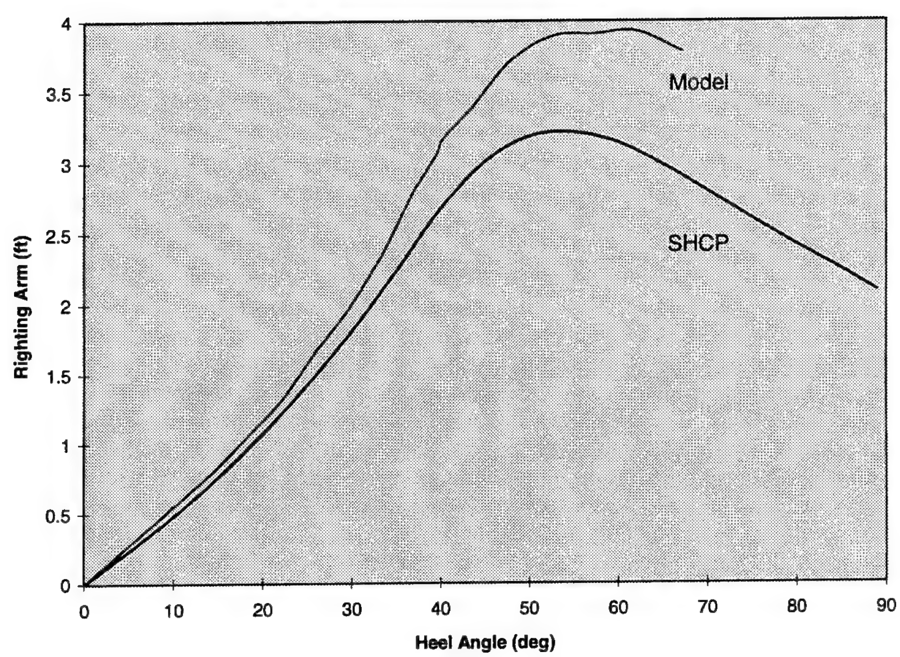

Figure 8. Righting Arm Curve Comparison: U-Tank, Outer Shell Damaged

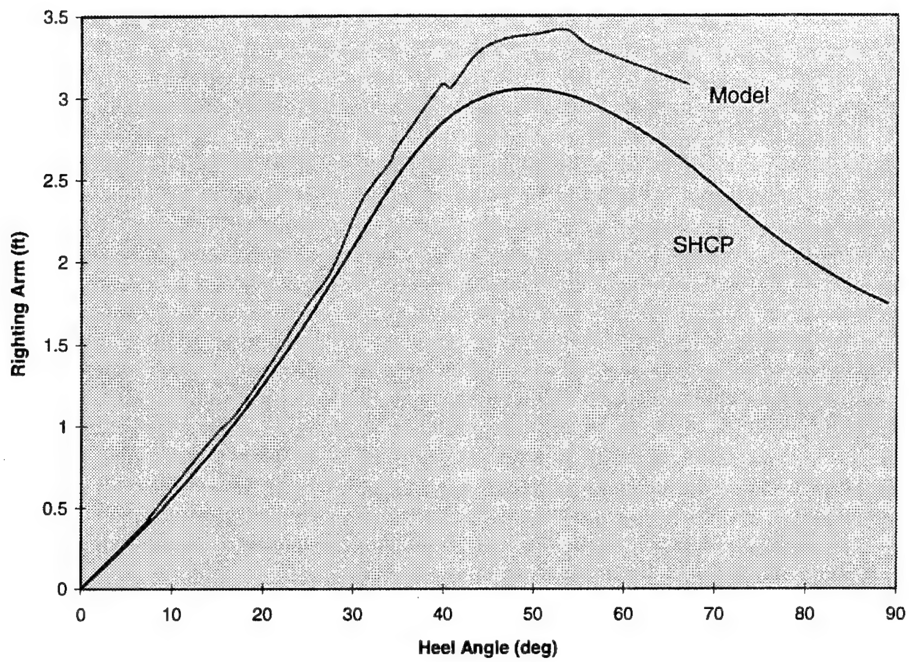

Figure 9. Righting Arm Curve Compariosn: U-Tank, Outer and Inner Shells Damage

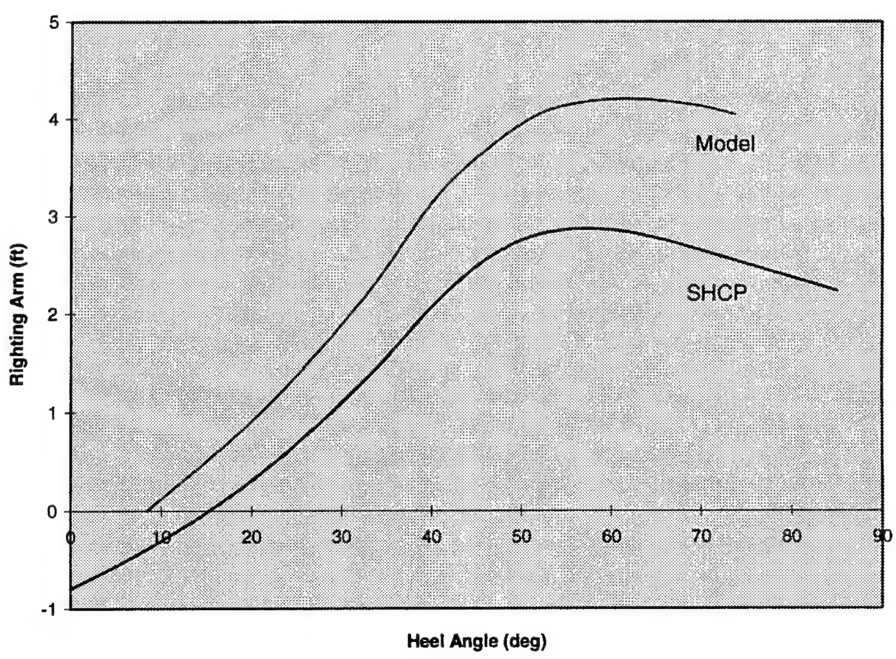

Figure 10. Righting Arm Curve Comparison: J-Tank, Outer Shell Damaged

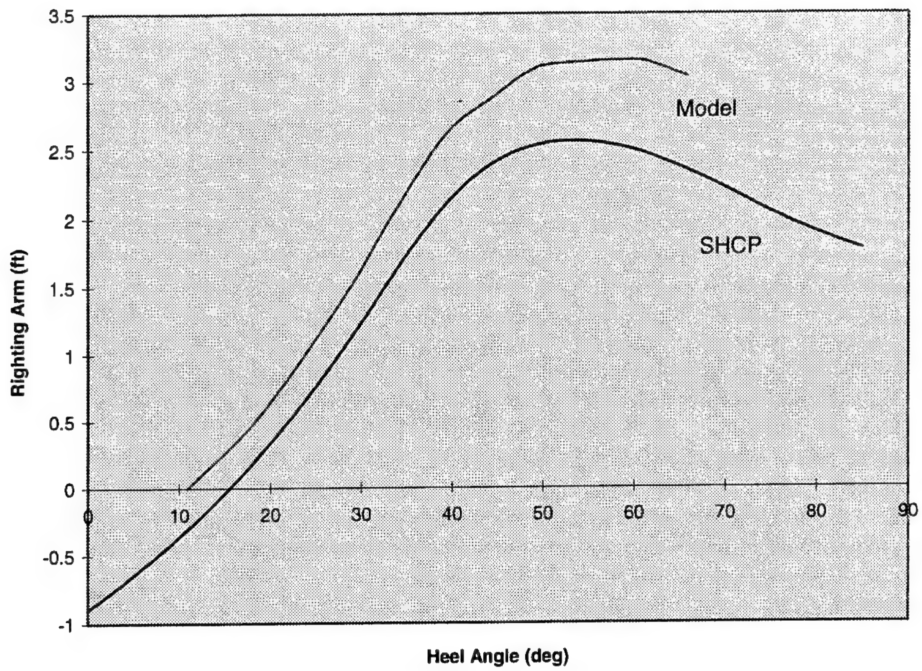

Figure 11. Righting Arm Curve Comparison: J-Tank, Outer and Inner Shells Damaged

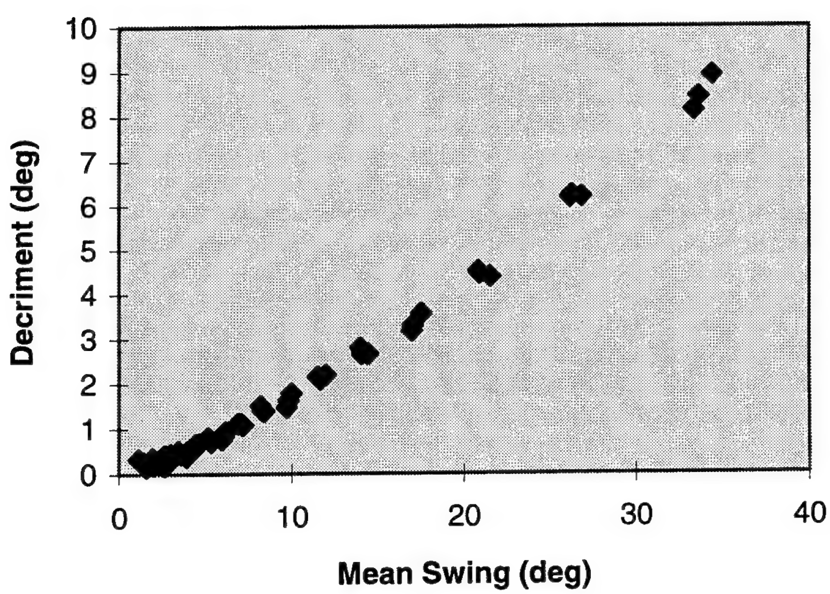

Figure 12. Roll Extinction Data: Intact Condition

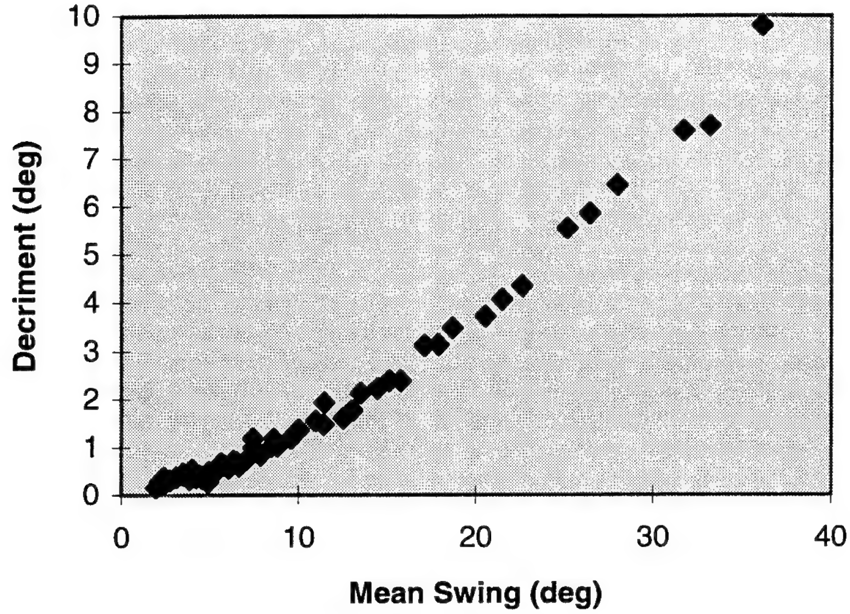

Figure 13. Roll Extinction Data: U-Tank, Outer Shell Damaged

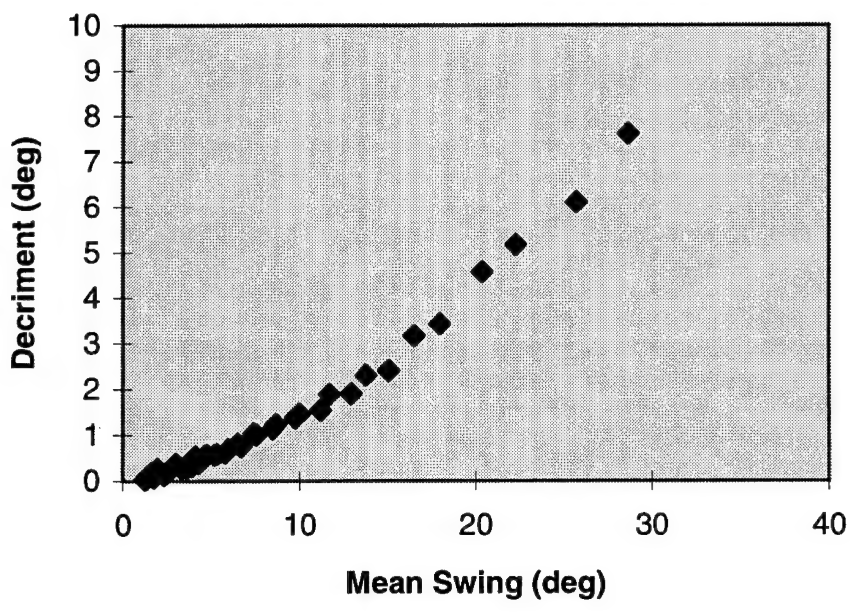

Figure 14. Roll Extinction Data: U-Tank, Outer and Inner Shells Damaged

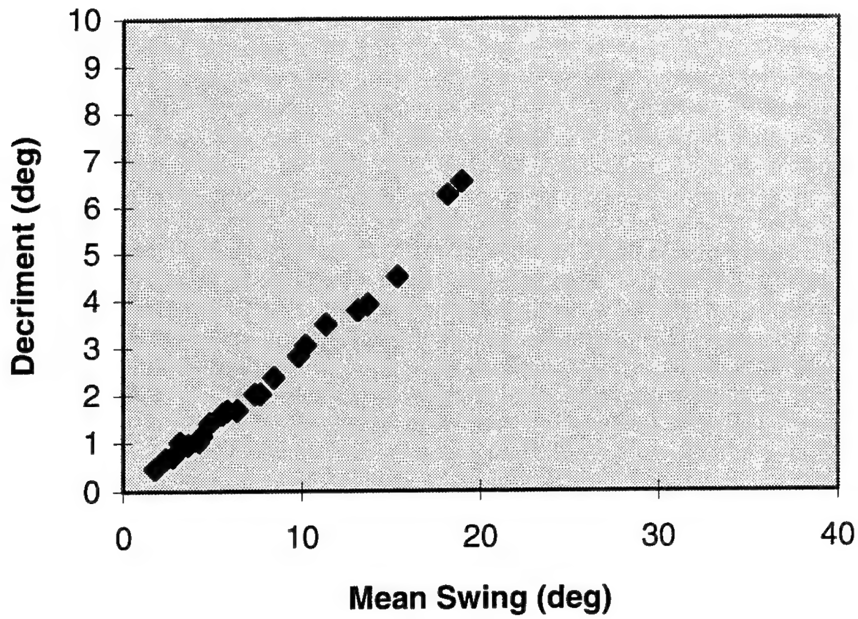

Figure 15. Roll Extinction Data: J-Tank, Outer Shell Damaged

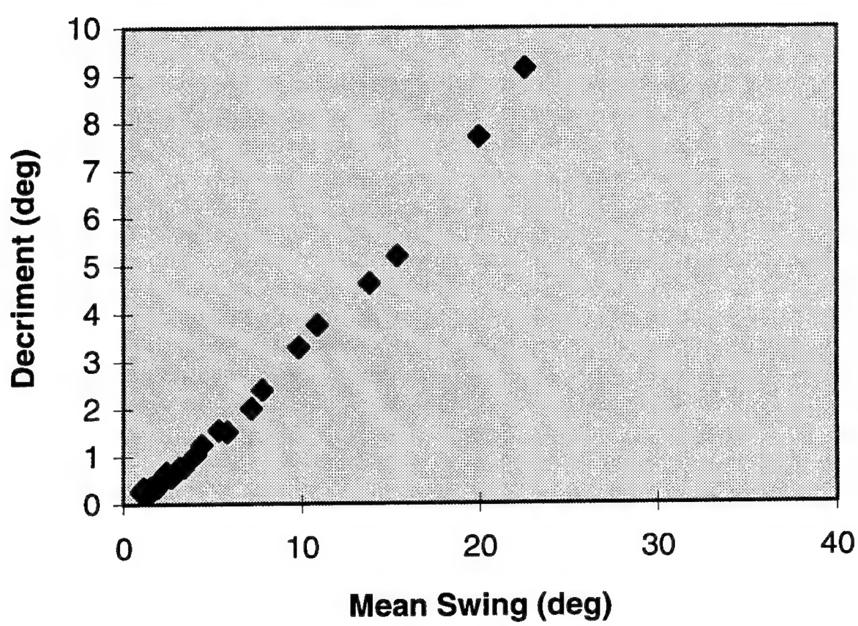

Figure 16. Roll Extinction Data: J-Tank, Outer and Inner Shells Damaged

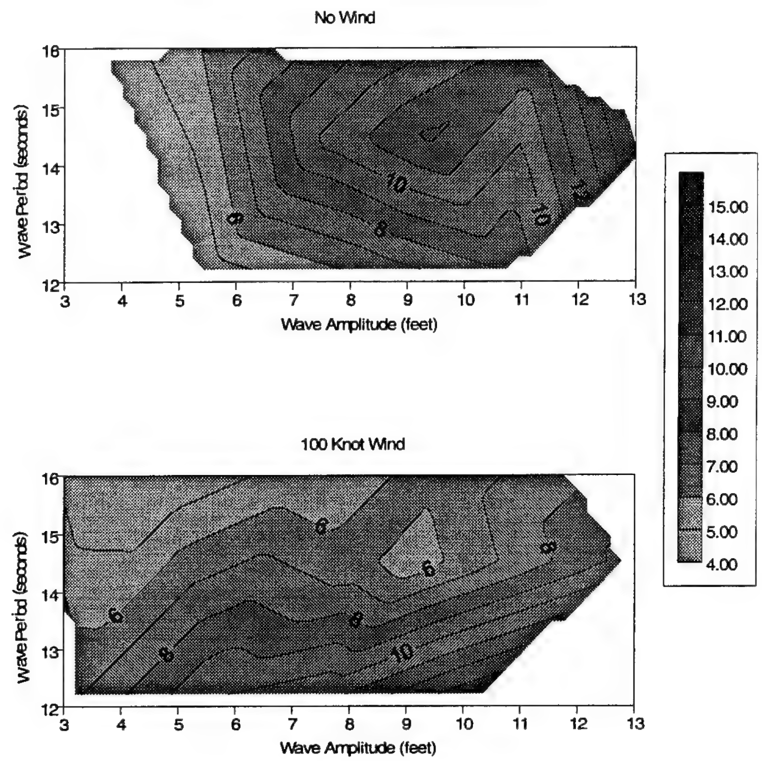

Figure 17. Extreme Roll Response Contours About the Mean, Intact Condition

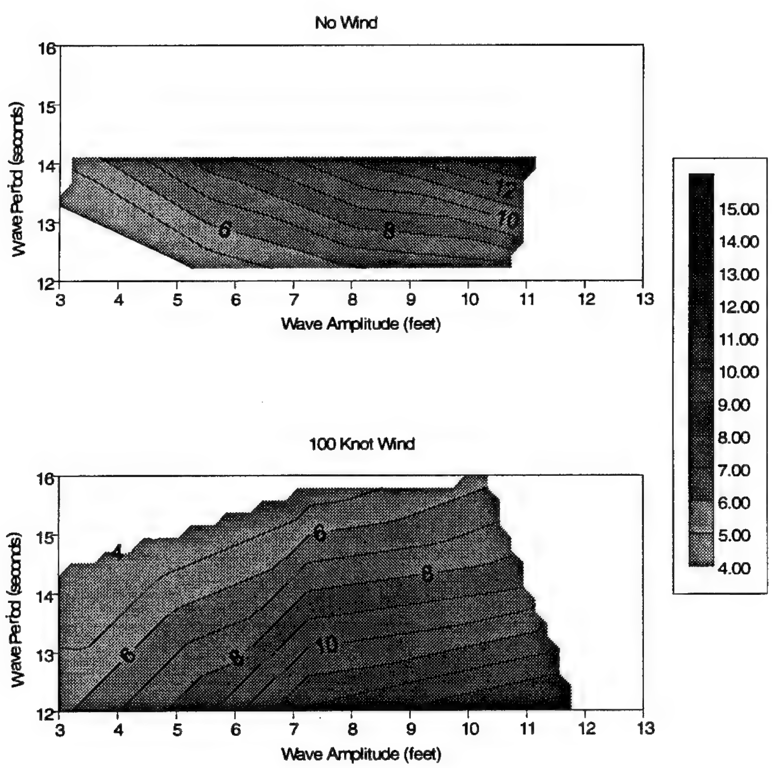

Figure 18. Extreme Roll Response Contours About the Mean, U-Tank, Outer Shell Damage

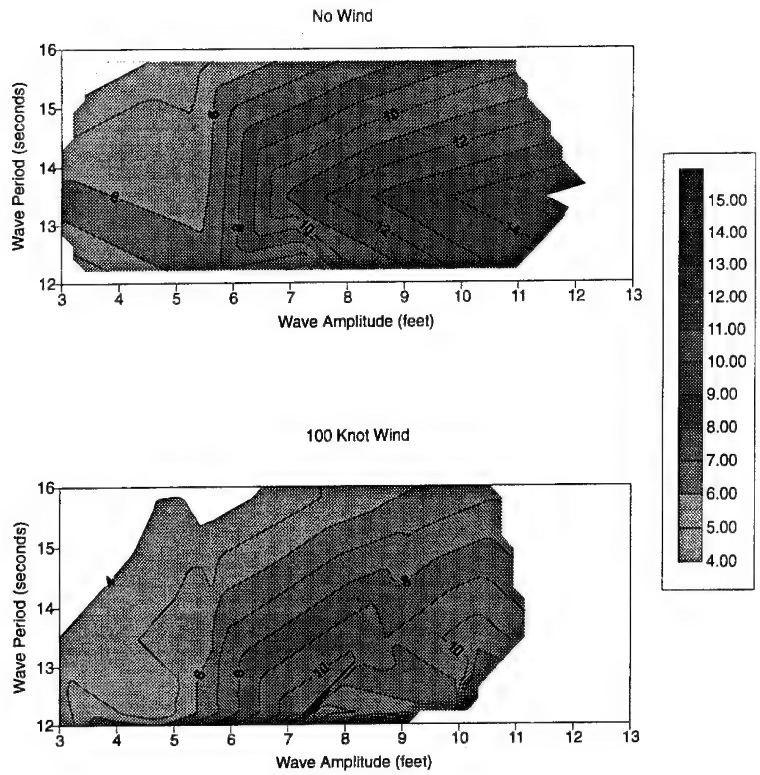

Figure 19. Extreme Roll Response Contours About the Mean, U-Tank, Outer and Inner Shells Damage

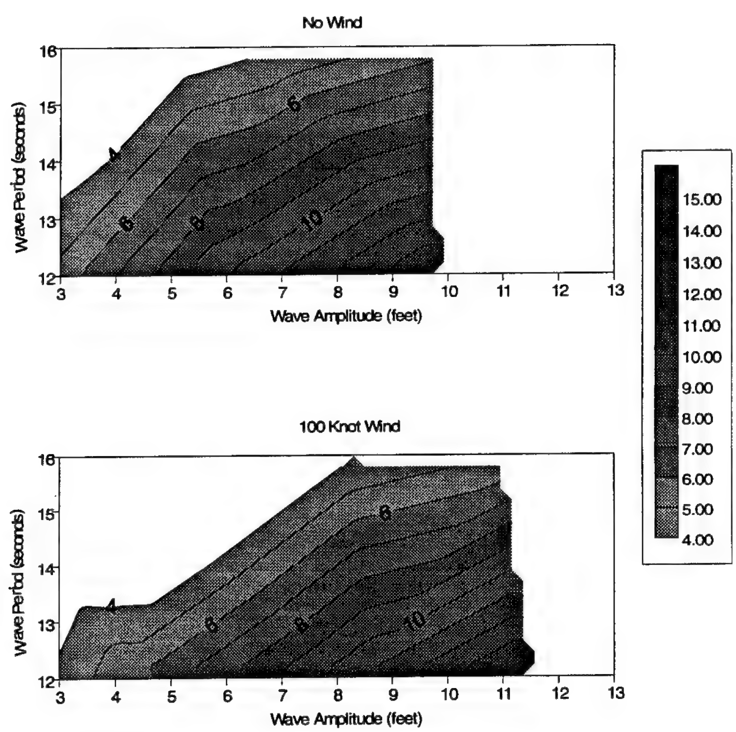

Figure 20. Extreme Roll Response ContoursAbout the Mean, J-Tank, Outer Shell Damage

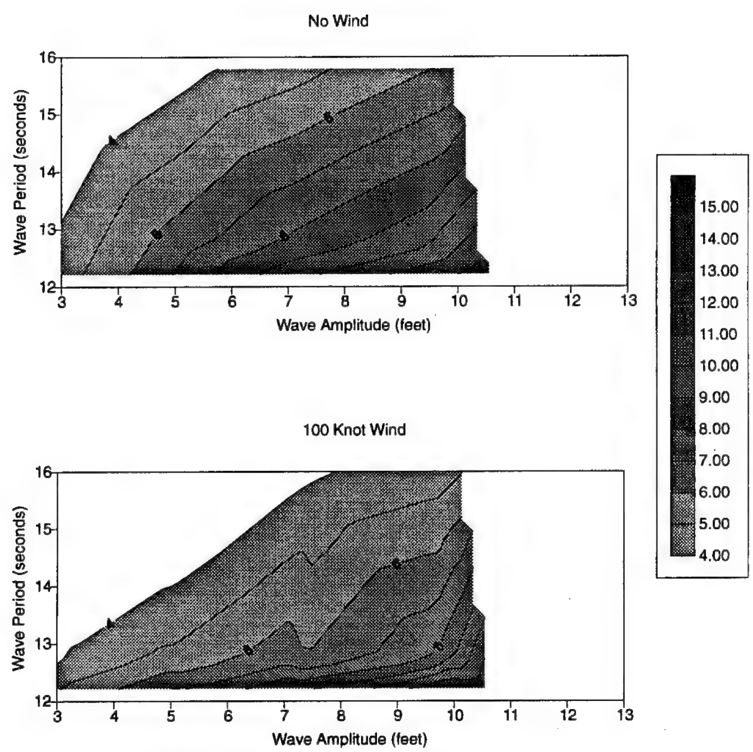

Figure 21. Extreme Roll Response Contours About the Mean, J-Tank, Outer and Inner Shells Damage

Table 1. Ship Particulars

	Full Scale	Model Scale
LPP (ft/m)	529 / 161.2	21.31 / 6.50
LWL (ft/m)	530 / 161.5	21.35 / 6.51
Displacement (LTSW/MTSW)	9561.26 / 9714.24	0.608 / 0.618
Draft (ft/m)	22.22 / 6.77	0.895 / 0.273
LCG (ft/m +fwd midship)	-9.89 / 3.01	-0.398 / -0.121
KG (ft/m)	23.42 / 7.14	0.943 / 0.287
GM (intact, ft/m)	2.647 / 0.807	0.107 / 0.033

Table 2. Righting Arm Validation Test Error Analysis

Error Source	Load Cell 1 (lbf) bias	Load Cell 1 (lbf) random	Load Cell 2 (lbf) bias	Load Cell 2 (lbf) random	Inclinometer (deg) bias	Inclinometer (deg) random
Cal Standard	-	1.138E-02	-	1.138E-02	-	-
Alignment	-	-	-	-	-	9.800E-02
Zero Ref	-	-	-	-	5.000E-01	1.005E+00
TOTAL CAL. RSS	-	1.138E-02	-	1.138E-02	5.000E-01	1.010E+00
Load Cell	2.000E-01	-	2.000E-01	-	-	-
A/D conversion	-	-	-	-	-	-
TOTAL ACQ. RSS	2.000E-01	-	2.000E-01	-	-	-
TOTAL RSS	2.000E-01	1.138E-02	2.000E-01	1.138E-02	5.000E-01	1.010E+00
UADD - 99%	**2.228E-01**		**2.228E-01**		**2.52E+00**	
URSS - 95%	**2.013E-01**		**2.013E-01**		**2.08E+00**	

Analysis Errors

Error Source	bias	random
Ring Diameter (ft)	0.0416667	-
Load Summation (lbf)	0.2828427	0.016088
TOTAL (ft-lbf)	0.2858953	0.016088
ERROR ON R.A.		
UADD - 99% (ft)	**0.3180713**	
URSS - 95% (ft)	**0.2877002**	
ERROR AN HEEL		
UADD - 99% (deg)	**2.52E+00**	
URSS - 95% (deg)	**2.08E+00**	

Table 3. Roll Decay And Regular Wave Test Error Analysis

Error Source	Roll Angle (deg) bias	Roll Angle (deg) random	Heave accel. (g's) bias	Heave accel. (g's) random	Wave probe (inches) bias	Wave probe (inches) random
Cal Standard	-	-	-	-	2.500E-01	-
Alignment	-	7.753E-02	-	2.741E-02	-	-
Zero Ref	3.000E-01	6.000E-01	-	1.000E-01	-	1.600E-01
TOTAL CAL. RSS	3.000E-01	6.050E-01	-	1.037E-01	2.500E-01	1.600E-01
A/D conversion	1.465E-02	-	1.074E-03	-	1.953E-02	-
TOTAL ACQ. RSS	1.465E-02	-	1.074E-03	-	1.953E-02	-
TOTAL RSS	3.004E-01	6.050E-01	1.074E-03	1.037E-01	2.508E-01	1.600E-01
UADD - 99%	**1.510E+00**		**2.085E-01**		**5.71E-01**	
URSS - 95%	**1.247E+00**		**2.074E-01**		**4.07E-01**	

Table 4. Measured and Predicted Static Heel Angles and Deck at Edge Immersion Angles

	Measured Static Heel Angle (deg)	Predicted Static Heel Angle (deg)	Measured Deck at Edge Immersion Angle (deg)	Predicted Deck at Edge Immersion Angle (deg)
Intact	0.0	0.0	37.6	37.2
U-Tank	0.0	0.0	35.7	34.1
U-Tank w/Internal Shell Damage	-NA-	-NA-	-NA-	-NA-
J-Tank	8.4	14.5	37.5	35.0
J-Tank w/Internal Shell Damage	10.9	14.9	33.4	29.5

Table 5. Linear Damping Coefficients and Mean Natural Roll Periods

	Linear Roll Damping Coefficient	Percent Change from Intact Linear Roll Damping	Mean Natural Roll Period (sec)
Intact	0.03768	0	14.44
U-Tank	0.02500	-33.65%	14.08
U-Tank w/Internal Shell Damage	0.02265	-39.89%	14.27
J-Tank	0.09657	156.29%	12.45
J-Tank w/Internal Shell Damage	0.07478	98.46%	12.60

Table 6. Regular Wave Test Results, No Wind

Intact Condition

Run	Mean WH (in MS)	Wave Ht (in MS)	Period (sec MS)	Mean Roll (deg)	Nom. Ext. Roll (deg)	Roll Period (sec MS)	Roll Offset	Wave Ht (ft FS)	Period (sec FS)	Mean Roll (deg)	Ext. Roll (deg)	Roll Period (sec FS)
62	-0.155	2.596	2.418	-0.617	4.094	2.422	0	5.369	12.046	-0.617	4.094	12.068
63	-0.108	4.087	2.418	-0.799	6.072	2.421	0	8.455	12.048	-0.799	6.072	12.065
64	-0.082	5.198	2.417	-0.936	7.712	2.412	0	10.752	12.042	-0.936	7.712	12.016
65	-0.154	3.629	2.894	-0.762	10.199	2.901	0	7.508	14.417	-0.762	10.199	14.454
66	-0.166	4.518	2.904	-0.685	12.225	2.903	0	9.346	14.467	-0.685	12.225	14.465
67	-0.139	6.600	2.905	-0.664	16.782	2.898	0	13.653	14.476	-0.664	16.782	14.441
68	-0.151	1.742	3.201	-0.743	4.195	3.192	0	3.603	15.948	-0.743	4.195	15.903
69	-0.152	2.586	3.216	-0.791	5.914	3.204	0	5.349	16.022	-0.791	5.914	15.961
70	-0.173	3.820	3.206	-0.718	8.693	3.190	0	7.901	15.973	-0.718	8.693	15.895
71	-0.162	5.394	3.197	-0.794	11.473	3.188	0	11.158	15.931	-0.794	11.473	15.885
max								13.653	16.022	-0.617	16.782	15.961
min								3.603	12.042	-0.936	4.094	12.016

U-Tank w/ internal shell damage

Run	Mean WH (in MS)	Wave Ht (in MS)	Period (sec MS)	Mean Roll (deg)	Nom. Ext. Roll (deg)	Roll Period (sec MS)	Roll Offset	Wave Ht (ft FS)	Period (sec FS)	Mean Roll (deg)	Ext. Roll (deg)	Roll Period (sec FS)
75	-0.115	1.646	2.415	-0.272	4.225	2.414	0	3.406	12.030	-0.272	4.225	12.026
76	-0.083	2.708	2.417	-0.451	6.403	2.418	0	5.602	12.044	-0.451	6.403	12.046
77	-0.099	3.930	2.419	-0.676	9.453	2.412	0	8.130	12.054	-0.676	9.453	12.016
78	-0.123	5.318	2.416	-1.400	13.055	2.405	0	11.002	12.039	-1.400	13.055	11.981
79	-0.101	1.707	3.185	-0.253	3.061	3.192	0	3.531	15.867	-0.253	3.061	15.904
80	-0.127	2.561	3.186	-0.223	4.501	3.178	0	5.297	15.872	-0.223	4.501	15.836
81	-0.153	3.752	3.196	-0.221	6.629	3.198	0	7.762	15.924	-0.221	6.629	15.935
82	-0.167	5.253	3.203	-0.307	9.028	3.203	0	10.866	15.958	-0.307	9.028	15.956
83	-0.091	3.389	2.701	-0.384	11.361	2.704	0	7.011	13.456	-0.384	11.361	13.472
84	-0.122	4.226	2.705	-0.516	13.358	2.704	0	8.741	13.476	-0.516	13.358	13.472
85	-0.075	5.966	2.708	-0.812	15.543	2.707	0	12.342	13.491	-0.812	15.543	13.485
86	-0.091	1.268	2.700	-0.206	6.293	2.704	0	2.624	13.453	-0.206	6.293	13.471
123	0.352	3.588	2.419	-1.254	4.876	2.419	0	7.422	12.053	-1.254	4.876	12.052
max								12.342	15.958	-0.206	15.543	15.956
min								2.624	12.030	-1.400	3.061	11.981

J-Tank w/ internal shell damage

Run	Mean WH (in MS)	Wave Ht (in MS)	Period (sec MS)	Mean Roll (deg)	Nom. Ext. Roll (deg)	Roll Period (sec MS)	Roll Offset	Wave Ht (ft FS)	Period (sec FS)	Mean Roll (deg)	Ext. Roll (deg)	Roll Period (sec FS)
137	0.2456	1.4507	2.4204	-10.8056	4.7063	2.4152	0	3.001	12.059	-10.806	4.706	12.033
138	0.2609	1.6338	2.4226	-10.8306	5.0904	2.4109	0	3.380	12.070	-10.831	5.090	12.012
139	0.2646	3.5792	2.4207	-10.8068	10.3076	2.4083	0	7.404	12.061	-10.807	10.308	11.999
140	0.2895	5.1368	2.4186	-11.0215	13.0543	2.3993	0	10.626	12.050	-11.022	13.054	11.954
141	0.2955	1.3722	2.5611	-10.8595	4.0499	2.5447	0	2.839	12.760	-10.860	4.050	12.679
142	0.3111	2.3641	2.5554	-10.8025	6.3889	2.5443	0	4.891	12.732	-10.803	6.389	12.677
143	0.3257	3.4153	2.5536	-10.8129	8.2665	2.5441	0	7.065	12.723	-10.813	8.267	12.676
144	0.3266	4.5089	2.5602	-10.8888	9.6800	2.5379	0	9.327	12.756	-10.889	9.680	12.645
145	0.3097	1.3318	3.1938	-10.8854	1.9619	3.1687	0	2.755	15.913	-10.885	1.962	15.788
146	0.3277	2.6347	3.2118	-10.9273	3.6038	3.1912	0	5.450	16.003	-10.927	3.604	15.900
147	0.3488	3.4713	3.1567	-10.8136	4.7049	3.1599	0	7.181	15.728	-10.814	4.705	15.744
148	0.3261	4.8535	3.1695	-10.8204	6.2746	3.1869	0	10.040	15.792	-10.820	6.275	15.878
max								10.626	16.003	-10.803	13.054	15.900
min								2.755	12.050	-11.022	1.962	11.954

Table 6. (Continued)

J-Tank

Run	Mean WH (in MS)	Wave Ht (in MS)	Period (sec MS)	Mean Roll (deg)	Nom. Ext. Roll (deg)	Roll Period (sec MS)	Roll Offset	Wave Ht (ft FS)	Period (sec FS)	Mean Roll (deg)	Ext. Roll (deg)	Roll Period (sec FS)
178	-0.3630	1.2308	2.4181	-7.1561	4.7488	2.4190	0	2.546	12.048	-7.156	4.749	12.052
179	-0.3501	2.5267	2.4174	-7.1365	8.8078	2.4114	0	5.227	12.044	-7.137	8.808	12.015
180	-0.3561	3.1665	2.4107	-7.2685	10.6360	2.4083	0	6.550	12.011	-7.269	10.636	11.999
181	-0.3622	4.8103	2.4140	-7.4889	14.0137	2.4050	0	9.951	12.027	-7.489	14.014	11.982
182	-0.3716	1.2151	3.1944	-7.2036	1.6798	3.1873	0	2.514	15.916	-7.204	1.680	15.881
183	-0.3678	2.4818	3.1943	-7.2229	3.2223	3.1976	0	5.134	15.915	-7.223	3.222	15.932
184	-0.3492	3.3551	3.1712	-7.2136	4.2422	3.1745	0	6.941	15.800	-7.214	4.242	15.817
185	-0.3252	4.7770	3.1875	-7.2499	5.7823	3.1895	0	9.882	15.881	-7.250	5.782	15.891
186	-0.3552	0.9239	1.6057	-7.1971	0.8222	1.6097	0	1.911	8.000	-7.197	0.822	8.020
187	-0.3256	1.7367	1.6017	-7.1269	1.4142	1.6096	0	3.593	7.980	-7.127	1.414	8.019
188	-0.3023	2.8792	1.6008	-7.1447	2.3639	1.6232	0	5.956	7.976	-7.145	2.364	8.087
189	-0.3667	2.7852	2.4472	-7.1862	9.5750	2.4380	0	5.762	12.193	-7.186	9.575	12.147
190	-0.3371	4.6947	2.4468	-7.4716	13.7021	2.4323	0	9.712	12.191	-7.472	13.702	12.119
max								9.951	15.916	-7.127	14.014	15.932
min								1.911	7.976	-7.489	0.822	8.019

U-Tank

Run	Mean WH (in MS)	Wave Ht (in MS)	Period (sec MS)	Mean Roll (deg)	Nom. Ext. Roll (deg)	Roll Period (sec MS)	Roll Offset	Wave Ht (ft FS)	Period (sec FS)	Mean Roll (deg)	Ext. Roll (deg)	Roll Period (sec FS)
261	0.1356	1.4022	2.4304	-1.1682	2.2714	2.4380	0	2.901	12.109	-1.168	2.271	12.147
262	0.1476	2.6631	2.4203	-1.1242	3.9162	2.4268	0	5.509	12.059	-1.124	3.916	12.091
263	0.0865	3.7675	2.4154	-1.1956	5.3482	2.4136	0	7.794	12.034	-1.196	5.348	12.025
264	0.1476	5.2664	2.4201	-1.4472	6.2935	2.4213	0	10.894	12.058	-1.447	6.293	12.064
265	0.0745	1.4728	2.8387	-1.0936	5.2310	2.8353	0	3.047	14.143	-1.094	5.231	14.127
266	0.0850	2.6928	2.8417	-1.1048	8.7322	2.8305	0	5.571	14.158	-1.105	8.732	14.102
267	0.0901	4.0835	2.8367	-1.2170	11.7576	2.8288	0	8.447	14.133	-1.217	11.758	14.094
268	0.0858	5.4178	2.8315	-1.3400	14.8620	2.8251	0	11.208	14.107	-1.340	14.862	14.076
max								11.208	14.158	-1.094	14.862	14.127
min								2.901	12.034	-1.447	2.271	12.025

Table 7. Regular Wave Test Results, With Wind

Intact Condition

Run	Mean WH (in MS)	Wave Ht (in MS)	Period (sec MS)	Mean Roll (deg)	Nom. Ext. Roll (deg)	Roll Period (sec MS)	Fan Speed (rpm)	Roll Offset	Wave Ht (ft FS)	Period (sec FS)	Mean Roll (deg)	Ext. Roll (deg)	Roll Period (sec FS)	Wind (knots)
46	0.111	1.523	2.416	14.402	6.988	2.420	234.435	30	3.150	12.039	-15.598	6.988	12.057	99.869
47	0.128	2.754	2.417	15.617	10.259	2.415	231.490	30	5.697	12.040	-14.383	10.259	12.031	98.615
48	0.108	3.653	2.413	15.437	11.134	2.408	231.604	30	7.556	12.024	-14.563	11.134	11.999	98.664
49	0.143	4.904	2.414	15.888	14.269	2.413	231.611	30	10.145	12.027	-14.112	14.269	12.020	98.666
50	0.134	1.579	3.208	14.387	4.094	2.632	230.054	30	3.267	15.986	-15.613	4.094	13.114	98.003
51	0.133	2.316	3.220	14.985	4.012	2.468	230.491	30	4.791	16.045	-15.015	4.012	12.298	98.189
52	0.120	3.344	3.216	14.618	5.329	3.190	230.515	30	6.918	16.023	-15.383	5.329	15.896	98.199
53	0.134	4.616	3.212	14.977	6.283	3.000	230.838	30	9.550	16.002	-15.023	6.283	14.945	98.337
54	0.122	3.943	2.909	14.636	6.337	2.907	230.713	30	8.156	14.493	-15.364	6.337	14.483	98.284
55	0.093	4.389	2.903	14.943	5.375	2.760	231.102	30	9.080	14.463	-15.057	5.375	13.752	98.450
56	0.141	6.250	2.907	15.042	9.441	2.896	231.262	30	12.929	14.486	-14.958	9.441	14.427	98.518
57	0.141	1.166	4.003	14.089	3.417	2.341	236.544	30	2.412	19.943	-15.911	3.417	11.662	100.768
58	0.079	1.733	4.009	14.408	3.511	2.612	234.517	30	3.585	19.975	-15.593	3.511	13.012	99.904
59	0.194	2.664	4.003	14.593	2.483	2.148	231.865	30	5.512	19.945	-15.407	2.483	10.700	98.774
60	0.159	4.635	3.952	14.235	3.780	2.406	232.980	30	9.588	19.689	-15.765	3.780	11.986	99.250
max									12.929	19.975	-14.112	14.269	15.896	
min									2.412	12.024	-15.911	2.483	10.700	

U-Tank w/ internal shell damage

Run	Mean WH (in MS)	Wave Ht (in MS)	Period (sec MS)	Mean Roll (deg)	Nom. Ext. Roll (deg)	Roll Period (sec MS)	Fan Speed (rpm)	Roll Offset	Wave Ht (ft FS)	Period (sec FS)	Mean Roll (deg)	Ext. Roll (deg)	Roll Period (sec FS)	Wind (knots)
103	0.248	5.113	3.152	12.347	7.114	3.143	239.238	30	10.578	15.704	-17.653	7.114	15.661	62.202
107	0.134	1.638	2.422	14.631	6.308	2.427	238.792	30	3.388	12.068	-15.369	6.308	12.091	62.086
108	0.086	2.243	2.343	15.431	9.814	2.430	237.982	30	4.640	11.676	-14.569	9.814	12.107	61.875
109	0.166	3.498	2.420	15.550	11.057	2.404	236.153	30	7.237	12.057	-14.450	11.057	11.976	61.400
110	0.209	4.852	2.421	15.212	14.129	2.412	237.107	30	10.037	12.061	-14.788	14.129	12.017	61.648
111	0.099	1.404	2.703	14.774	3.963	2.527	235.573	30	2.904	13.465	-15.226	3.963	12.590	61.249
112	0.149	2.843	2.702	14.842	7.253	2.691	235.619	30	5.881	13.462	-15.159	7.253	13.408	61.261
113	0.150	4.082	2.697	14.958	10.093	2.679	236.081	30	8.444	13.437	-15.042	10.093	13.350	61.381
114	0.206	4.986	2.690	15.312	10.736	2.675	233.645	30	10.315	13.403	-14.688	10.736	13.325	60.748
115	0.108	1.673	3.145	15.076	2.908	2.429	234.521	30	3.461	15.669	-14.924	2.908	12.103	60.975
116	0.080	2.645	3.216	14.629	2.934	2.573	234.861	30	5.472	16.025	-15.371	2.934	12.817	61.064
117	0.178	3.759	3.216	14.586	5.262	2.898	234.684	30	7.775	16.025	-15.414	5.262	14.438	61.018
119	0.601	5.176	3.212	14.307	6.654	2.928	242.154	30	10.708	16.001	-15.693	6.654	14.586	62.960
120	0.437	1.513	2.424	22.236	4.127	2.547	161.213	30	3.130	12.078	-7.764	4.127	12.691	35.467
121	0.447	2.291	2.433	22.435	4.228	2.428	155.846	30	4.739	12.124	-7.565	4.228	12.098	34.286
124	0.446	3.530	2.411	-7.776	6.018	2.389	157.615	0	7.302	12.013	-7.776	6.018	11.903	34.675
125	0.457	4.767	2.424	-7.939	7.663	2.410	159.386	0	9.861	12.077	-7.939	7.663	12.008	35.065
126	0.382	1.169	2.408	-8.116	3.827	2.679	157.328	0	2.419	11.997	-8.116	3.827	13.350	34.612
127	0.373	2.803	2.701	-8.050	6.019	2.723	157.197	0	5.798	13.459	-8.050	6.019	13.569	34.583
128	0.417	4.161	2.706	-7.964	8.876	2.699	157.958	0	8.609	13.481	-7.964	8.876	13.447	34.751
129	0.322	5.469	2.706	-7.618	9.430	2.713	155.141	0	11.314	13.481	-7.618	9.430	13.516	34.131
130	0.353	1.726	3.220	-7.773	2.025	2.509	155.519	0	3.571	16.041	-7.773	2.025	12.502	34.214
131	0.366	2.428	3.179	-7.499	4.259	3.125	155.770	0	5.022	15.839	-7.499	4.259	15.568	34.269
132	0.371	3.618	3.182	-7.875	4.835	3.205	155.935	0	7.484	15.852	-7.875	4.835	15.967	34.306
133	0.332	4.393	3.151	-7.277	6.188	3.189	155.879	0	9.088	15.698	-7.277	6.188	15.890	34.293
max									11.314	16.041	-7.277	14.129	15.967	
min									2.419	11.676	-17.653	2.025	11.903	

Table 7. (Continued)

J-Tank w/ internal shell damage

Run	Mean WH (in MS)	Wave Ht (in MS)	Period (sec MS)	Mean Roll (deg)	Nom. Ext. Roll (deg)	Roll Period (sec MS)	Fan Speed (rpm)	Roll Offset	Wave Ht (ft FS)	Period (sec FS)	Mean Roll (deg)	Ext. Roll (deg)	Roll Period (sec FS)	Wind (knots)
150	0.357	1.407	2.419	-15.897	5.046	2.408	160.329	0	2.911	12.054	-15.897	5.046	11.999	23.729
151	0.358	2.538	2.419	-16.002	7.720	2.397	162.235	0	5.250	12.054	-16.002	7.720	11.945	24.011
152	0.361	3.855	2.417	-15.975	10.248	2.412	163.791	0	7.974	12.044	-15.975	10.248	12.016	24.241
153	0.344	5.207	2.419	14.719	12.772	2.406	158.287	30	10.772	12.055	-15.281	12.772	11.986	23.426
154	0.321	1.478	2.556	14.438	4.053	2.538	160.068	30	3.058	12.735	-15.563	4.053	12.643	23.690
155	0.350	2.323	2.554	14.282	5.213	2.528	156.716	30	4.805	12.726	-15.718	5.213	12.598	23.194
156	0.321	3.385	2.555	14.686	6.559	2.531	157.514	30	7.003	12.731	-15.315	6.559	12.613	23.312
157	0.369	4.821	2.559	14.880	8.912	2.537	155.652	30	9.972	12.748	-15.120	8.912	12.642	23.037
158	0.320	1.423	3.191	14.608	1.864	2.616	156.194	30	2.944	15.900	-15.392	1.864	13.032	23.117
159	0.364	2.447	3.159	14.815	2.330	3.095	156.349	30	5.063	15.738	-15.186	2.330	15.419	23.140
160	0.424	3.700	3.201	14.606	3.959	3.206	156.744	30	7.653	15.947	-15.394	3.959	15.972	23.198
161	0.327	4.936	3.221	14.751	5.015	3.224	154.087	30	10.211	16.047	-15.249	5.015	16.064	22.805
163	0.317	1.545	2.423	9.598	5.477	2.432	230.491	30	3.197	12.072	-20.402	5.477	12.115	68.225
164	0.259	2.560	2.421	9.591	7.498	2.408	231.576	30	5.296	12.060	-20.409	7.498	11.999	68.546
165	0.280	3.500	2.421	10.119	9.585	2.418	231.179	30	7.240	12.063	-19.881	9.585	12.045	68.429
166	0.339	4.702	2.435	9.665	12.360	2.397	231.099	30	9.727	12.133	-20.335	12.360	11.944	68.405
167	0.315	1.400	2.556	9.455	3.231	2.541	230.858	30	2.896	12.737	-20.545	3.231	12.660	68.334
168	0.244	2.451	2.549	9.530	5.281	2.542	230.877	30	5.069	12.698	-20.470	5.281	12.664	68.340
169	0.283	3.557	2.556	9.709	6.014	2.554	232.813	30	7.357	12.737	-20.291	6.014	12.727	68.913
170	0.356	4.647	2.554	9.308	7.922	2.536	232.916	30	9.613	12.724	-20.692	7.922	12.636	68.943
171	0.296	1.351	3.190	9.075	1.784	2.234	232.698	30	2.794	15.895	-20.925	1.784	11.132	68.879
172	0.306	2.387	3.187	9.348	2.579	2.591	232.732	30	4.937	15.878	-20.652	2.579	12.910	68.889
173	0.311	3.489	3.222	9.549	3.629	2.369	233.066	30	7.218	16.052	-20.451	3.629	11.804	68.988
174	0.370	4.751	3.181	9.675	4.721	3.171	232.999	30	9.828	15.847	-20.325	4.721	15.797	68.968
max									10.772	16.052	-15.120	12.772	16.064	
min									2.794	12.044	-20.925	1.784	11.132	

J-Tank

Run	Mean WH (in MS)	Wave Ht (in MS)	Period (sec MS)	Mean Roll (deg)	Nom. Ext. Roll (deg)	Roll Period (sec MS)	Fan Speed (rpm)	Roll Offset	Wave Ht (ft FS)	Period (sec FS)	Mean Roll (deg)	Ext. Roll (deg)	Roll Period (sec FS)	Wind (knots)
192	-0.335	1.524	2.416	-12.089	6.660	2.406	164.845	0	3.153	12.036	-12.089	6.660	11.985	22.584
193	-0.302	2.623	2.415	-11.868	8.137	2.403	161.800	0	5.427	12.032	-11.868	8.137	11.971	22.167
194	-0.302	3.680	2.414	-12.341	10.683	2.399	163.029	0	7.613	12.027	-12.341	10.683	11.951	22.335
195	-0.288	3.806	2.417	-12.428	10.805	2.410	165.743	0	7.874	12.045	-12.428	10.805	12.010	22.707
196	-0.297	5.629	2.419	-12.161	14.506	2.409	160.837	0	11.645	12.052	-12.161	14.506	12.005	22.035
197	-0.386	1.273	3.215	-12.757	2.153	2.419	161.439	0	2.634	16.017	-12.757	2.153	12.054	22.117
198	-0.358	2.458	3.207	-12.689	2.944	3.076	161.809	0	5.084	15.976	-12.689	2.944	15.328	22.168
199	-0.238	3.455	3.212	-12.150	4.177	3.196	157.487	0	7.148	16.003	-12.150	4.177	15.923	21.576
200	-0.269	4.992	3.170	-12.119	5.292	3.162	157.542	0	10.326	15.793	-12.119	5.292	15.754	21.583
201	-0.315	1.595	1.609	-12.492	2.372	1.769	157.098	0	3.299	8.015	-12.492	2.372	8.815	21.522
202	-0.271	2.098	1.605	-11.999	2.247	1.737	157.214	0	4.339	7.996	-11.999	2.247	8.654	21.538
203	-0.282	3.310	1.608	-11.894	3.511	1.648	157.343	0	6.847	8.010	-11.894	3.511	8.212	21.556
204	-0.324	2.209	2.450	-12.863	6.546	2.420	157.438	0	4.570	12.205	-12.863	6.546	12.058	21.569
205	-0.307	3.938	2.451	-12.808	10.887	2.429	157.517	0	8.146	12.212	-12.808	10.887	12.101	21.580
206	-0.279	5.299	2.447	-12.831	13.455	2.433	157.567	0	10.961	12.193	-12.831	13.455	12.120	21.587
208	0.254	1.523	2.013	12.562	5.817	2.413	243.036	30	3.151	10.030	-17.438	5.817	12.023	63.189
209	0.227	1.276	1.999	12.766	5.001	2.399	242.092	30	2.639	9.959	-17.234	5.001	11.951	62.944
211	0.170	2.076	2.426	12.161	5.817	2.414	239.817	30	4.294	12.089	-17.839	5.817	12.026	62.353
212	0.261	4.025	2.425	12.801	10.704	2.419	241.134	30	8.327	12.080	-17.199	10.704	12.051	62.695
213	0.411	5.493	2.417	12.789	14.540	2.406	241.887	30	11.362	12.043	-17.212	14.540	11.989	62.891
214	0.110	1.212	2.890	12.638	2.254	1.996	239.646	30	2.506	14.398	-17.362	2.254	9.942	62.308
215	0.089	2.410	2.923	12.710	2.123	2.507	240.929	30	4.985	14.565	-17.290	2.123	12.490	62.642
216	0.022	3.953	3.212	12.690	3.748	2.576	237.352	30	8.177	16.005	-17.310	3.748	12.834	61.712
217	0.120	5.345	3.203	12.894	5.076	3.194	239.044	30	11.057	15.956	-17.106	5.076	15.914	62.152
218	0.076	1.320	1.518	12.732	2.612	1.782	239.316	30	2.731	7.563	-17.269	2.612	8.880	62.222
219	0.080	2.221	1.600	12.888	4.391	1.697	239.752	30	4.595	7.970	-17.112	4.391	8.457	62.336
220	0.192	3.161	1.605	13.138	5.615	1.609	240.514	30	6.540	7.998	-16.862	5.615	8.015	62.534
221	0.111	2.211	2.447	12.746	5.946	2.432	238.740	30	4.574	12.190	-17.254	5.946	12.116	62.072
222	0.116	4.199	2.448	13.335	10.930	2.432	238.723	30	8.687	12.198	-16.665	10.930	12.116	62.068
223	0.165	5.615	2.448	13.109	13.656	2.435	239.062	30	11.616	12.196	-16.891	13.656	12.133	62.156
max									11.645	16.017	-11.868	14.540	15.923	
min									2.506	7.563	-17.839	2.123	8.015	

Table 7. (Continued)

U-Tank

Run	Mean WH (in MS)	Wave Ht (in MS)	Period (sec MS)	Mean Roll (deg)	Nom. Ext. Roll (deg)	Roll Period (sec MS)	Fan Speed (rpm)	Roll Offset	Wave Ht (ft FS)	Period (sec FS)	Mean Roll (deg)	Ext. Roll (deg)	Roll Period (sec FS)	Wind (knots)
229	0.121	1.273	2.163	15.733	5.293	2.437	239.725	30	2.633	10.777	-14.267	5.293	12.143	75.993
230	0.181	2.724	2.409	16.669	9.026	2.409	240.078	30	5.635	12.002	-13.331	9.026	12.003	76.105
231	0.129	3.496	2.414	16.204	12.158	2.429	240.267	30	7.232	12.030	-13.796	12.158	12.100	76.165
236	0.097	1.115	2.869	-16.184	4.272	2.576	237.785	0	2.307	14.295	-16.184	4.272	12.832	75.378
237	0.166	3.540	3.187	-16.243	4.199	2.637	238.889	0	7.322	15.877	-16.243	4.199	13.136	75.728
238	0.131	2.157	2.998	-16.297	3.848	2.931	239.640	0	4.462	14.939	-16.297	3.848	14.606	75.966
239	0.195	5.020	3.216	-16.341	5.672	3.185	240.380	0	10.385	16.022	-16.341	5.672	15.869	76.200
240	0.270	1.074	1.070	-15.774	4.680	2.287	240.970	0	2.222	5.332	-15.774	4.680	11.395	76.388
241	0.319	1.200	1.582	-16.283	3.790	2.431	241.096	0	2.483	7.884	-16.283	3.790	12.110	76.427
242	0.322	1.922	1.739	-15.997	5.870	2.799	241.241	0	3.977	8.663	-15.997	5.870	13.944	76.473
243	0.387	2.818	2.061	-16.010	7.113	2.532	241.420	0	5.830	10.269	-16.010	7.113	12.614	76.530
244	0.058	5.321	2.838	-15.703	8.888	2.813	238.609	0	11.008	14.141	-15.703	8.888	14.015	75.639
245	0.055	5.792	2.414	-15.473	14.730	2.409	243.571	0	11.982	12.029	-15.473	14.730	12.005	77.212
246	0.067	1.424	2.414	-16.432	5.641	2.339	245.514	0	2.946	12.029	-16.432	5.641	11.653	77.828
247	0.120	1.648	2.413	-7.507	4.955	2.665	161.438	0	3.409	12.025	-7.507	4.955	13.280	41.974
248	0.127	2.693	2.415	-7.783	3.946	2.404	161.791	0	5.571	12.035	-7.783	3.946	11.977	42.066
249	0.152	3.688	2.417	-7.230	5.206	2.401	156.953	0	7.629	12.042	-7.230	5.206	11.965	40.808
250	0.126	5.238	2.442	-7.105	7.313	2.428	157.095	0	10.835	12.165	-7.105	7.313	12.099	40.845
251	0.109	1.366	2.833	-7.157	2.433	2.693	157.235	0	2.826	14.116	-7.157	2.433	13.417	40.881
252	0.079	2.726	2.846	-7.254	4.367	2.837	157.324	0	5.638	14.182	-7.254	4.367	14.134	40.904
253	0.119	3.506	2.831	-7.186	6.285	2.853	157.285	0	7.254	14.105	-7.186	6.285	14.215	40.894
254	0.142	4.358	2.837	-7.213	9.520	2.825	157.364	0	9.015	14.133	-7.213	9.520	14.074	40.915
255	0.120	5.568	2.840	-6.994	11.210	2.837	157.349	0	11.519	14.149	-6.994	11.210	14.135	40.911
256	0.105	1.287	3.216	-7.248	4.676	3.095	157.429	0	2.662	16.023	-7.248	4.676	15.421	40.931
257	0.075	2.642	3.216	-7.155	4.374	3.194	157.571	0	5.466	16.024	-7.155	4.374	15.916	40.968
258	0.109	3.593	3.192	-7.228	5.485	3.250	157.561	0	7.432	15.906	-7.228	5.485	16.191	40.966
259	0.059	4.813	3.191	-7.038	7.327	3.190	157.744	0	9.956	15.901	-7.038	7.327	15.893	41.013
max									11.982	16.024	-6.994	14.730	16.191	
min									2.222	5.332	-16.432	2.433	11.395	

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